

Breakthrough in Microscope Resolution

"Beating" the Bohr Radius

Using a newly developed transmission electron aberration-corrected microscope ("TEAM 0.5"), researchers at the National Center for Electron Microscopy at LBNL have established a new standard by resolving atoms separated by a distance that is less than the characteristic size of a hydrogen atom ("Bohr radius").

Although recent advances in electron optics have made sub-angstrom ($<0.1\text{ nm}; <10^{-10}\text{ m}$) imaging in transmission electron microscopy almost routine, a need remains to further improve spatial resolution to achieve increased sensitivity, image contrast, and the possibility of performing atomic-resolution tomography.

In the scanning transmission electron microscopy (STEM) mode used in these studies, the size of the electron probe that is focused onto the specimen ultimately limits the spatial resolution. This, in turn, is limited in principle by the electron's "de Broglie wavelength" (the wavelength of matter). For the 300-keV electrons typical in scanning transmission electron microscopy, that limit is about 2 pm ($2 \times 10^{-12}\text{ m}$), or 1/25th of the Bohr radius of hydrogen's 1s orbital. But STEM images are formed by focusing billions of electrons per second onto a sample. Aberrations of the electromagnetic lenses and the finite size of the electron source cause these electrons to lose phase coherence, lowering the resolution to about 100 pm, or about twice the distance between atoms in many crystalline orientations.

Previous efforts to improve the spatial resolution in STEM have mainly focused on minimizing phase shifts caused by lens aberrations. The TEAM development project also took into consideration the finite size of the electron source. Thus the TEAM microscope was designed with two novel components: a high-brightness electron source that emits copious numbers of electrons and a hexapole corrector that can compensate for phase aberrations up to fifth order.

The team performed resolution tests of the new microscope with a crystalline germanium foil in an orientation in which germanium atoms are arranged in rows of dumbbell pairs aligned end-to-end. The atom spacing in the dumbbell in this orientation is 47 pm. Ordinarily, the dumbbells are too small to be resolved with STEM. But the LBNL TEAM microscope could clearly resolve the 47-pm separation between paired atoms.

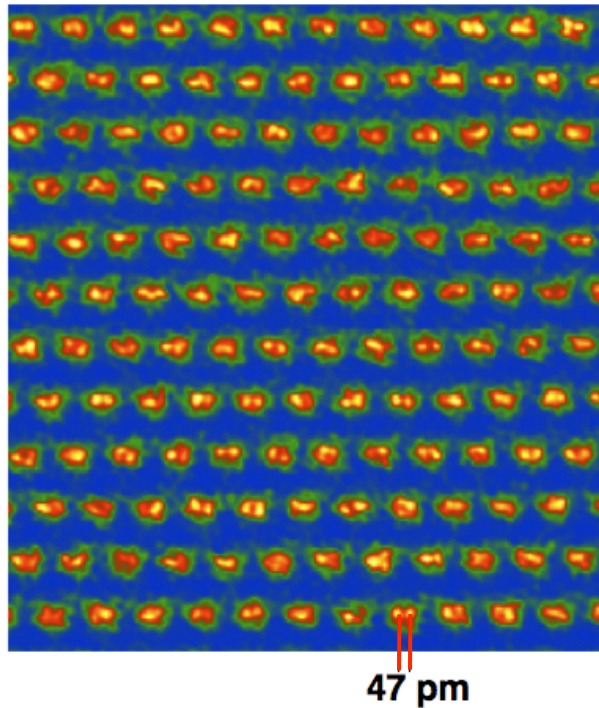
The TEAM images were compared to computer simulations to assess the ultimate resolution that is achievable with the microscope. Limiting factors include the 10 pm blurring due the thermal "jiggling" of the atoms during the room-temperature measurement. In addition, it was determined that specimen imperfections, including the presence of amorphous surface layers, surface roughness, or point defects, also reduced the resolution. Therefore, it was concluded that the sub-50-pm resolution achieved in the present result is not limited by the electron-optical setup of the TEAM microscope and therefore further improvements should be possible through the use of more perfect samples or cryogenic cooling.

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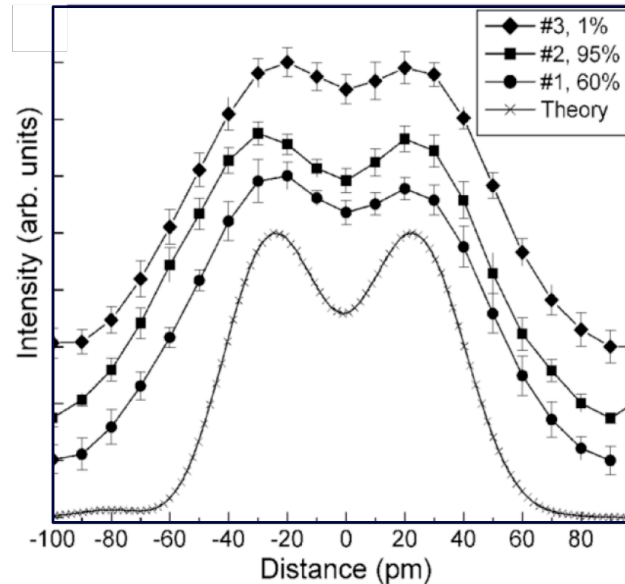
R. Erni, M. D. Rossell, C. Kisielowski, and U. Dahmen, "Atomic-Resolution Imaging with a Sub-50-pm Electron Probe," Phys. Rev. Lett. 102, 096101 (2009).

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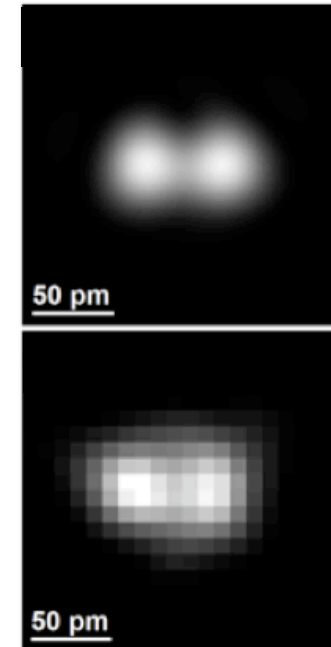
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Scanning electron microscopy image of a thin foil of germanium taken with the TEAM microscope. In this [114] crystalline orientation, the columns of Ge atoms are 47 pm apart. The Bohr radius of hydrogen atoms is 53 pm.



Line scans of selected dumbbells in the image and the comparison to theory. The probability of resolving the dumbbell structure into its two constituent Ge atoms in a single measurement are given. In some regions of the image, this probability is 95%.



Comparison of the calculated dumbbell image (above) and the average experimental dumbbell image.